Ann. Naturhist. Mus. Wien, Serie A	117	5–34	Wien, 15 Feb. 2015

Meteorite concentration sites in Queen Maud Land, Antarctica – a first assessment

By Georg DELISLE[1*], Franz BRANDSTÄTTER[2], Christian KOEBERL[3]

(With 9 figures and 2 tables)

Manuscript submitted on September 9th 2014,
the revised manuscript on November 11th 2014.

Abstract

Blue ice fields along the fringes of the Antarctic Plateau and along the Transantarctic Mountains are known as meteorite concentration sites. To assess the respective potential of blue ice fields in Queen Maud Land, a reconnaissance survey of a hitherto unexplored area to the southeast of the Wohlthat Massiv, Queen Maud Land, Antarctica was carried out in 2007 by the Queenmet–expedition of the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Germany. Three potential areas were viewed from the air and one site was visited. This site is made up by an elongated east –west trending topographic step with various blue ice fields along its shoulder. A meteorite concentration was found on its western termination as well as isolated finds. In total, 15 different meteorites were recovered, consisting of 14 stony meteorites and a 31 kg iron meteorite; they have been named after the Steingarden Nunataks (STG). All stony meteorites are ordinary chondrites, comprising 8 L chondrites, 5 H chondrites, and 1 LL chondrite. Results of rock exposure dating of rocks collected from local nunataks suggest a glaciological field situation that has little changed during the last ~0.5 Ma years. The find site of the Lazarev meteorite (found in 1961 by Russian workers) was searched from the air. Their field book with the geologic description of the find locality was re-analysed. We present arguments for an alternative find location of the Lazarev meteorite in comparison to the (probably inaccurate) coordinates repeatedly cited in the literature.

Keywords: meteorites, meteorite concentration, Antarctica, Queen Maud Land

[1] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655 Hannover, Germany; present address: Kiebitzweg 104, 30880 Laatzen, Germany; e-mail: g.delisle@t-online.de

[*] corresponding author

[2] Naturhistorisches Museum, Mineralogisch-Petrographische Abteilung, Burgring 7, 1010 Wien, Österreich; e-mail: franz.brandstaetter@nhm-wien.ac.at

[3] Naturhistorisches Museum, Burgring 7, 1010 Wien; and Department of Lithospheric Research, University of Vienna, Althanstrasse 14, 1090 Wien, Österreich; e-mail: christian.koeberl@univie.ac.at

Zusammenfassung

Blaueisfelder am Rande des antarktischen Polarplateaus repräsentieren potentielle Flächen mit Meteoritenansammlungen. Um das entsprechende Potential von Blaueisfeldern in Queen Maud Land zu untersuchen, wurde in 2007 die Queenmet-Expedition von der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, in ein bislang nicht untersuchtes Gebiet südöstlich des dortigen Wohlthat Massivs durchgeführt. Drei potentielle Untersuchungsgebiete wurden per Flugzeug erkundet und ein Gebiet untersucht. Dieses Gebiet ist charakterisiert durch eine ostwest ausgerichtete, ausgedehnte topographische Schwelle mit einer Reihe von Blauseisfeldern entlang ihrer Schulter. Eine Meteoritenkonzentration an ihrer westlichen Begrenzung wurde entdeckt. Zusätzlich erfolgten weitere Einzelfunde. Insgesamt 15 verschiedene Meteoriten wurden gesammelt, bestehend aus 14 Steinmeteoriten und einem 31 kg schweren Eisenmeteoriten; die Meteoriten wurden nach den Steingarden Nunataks (STG) benannt. Alle Steinmeteoriten sind gewöhnliche Chondrite und umfassen 8 L-Chondrite, 5 H-Chondrite und 1 LL-Chondrit. Gemessene Freilegungsalter von Gestein, entnommen von lokalen Nunatakern legen eine glaziologische Feldsituation nahe, die sich während der letzten ~500.000 Jahre wenig verändert hat. Die von russischen Forschern angegebene Fundstelle des 1961 geborgenen Meteoriten Lazarev wurde überflogen. Deren Feldbuch mit Angaben zur geologischen Situation an der Fundstelle wurde reanalysiert. Wir präsentieren Argumente für eine alternative Fundstelle des Lazarev-Meteoriten im Vergleich zu dem durch die mutmaßlich ungenauen Koordinaten definierten Punkt, der wiederholt in der Literatur zitiert wurde.

Schlüsselwörter: Meteoriten, Meteoritenkonzentration, Blaueisfelder, Antarktis, Queen Maud Land

Introduction

Meteorite concentration sites on blue ice in Antarctica occur along the Transantarctic Mountains, near the Sør Rondane Mountains, Queen Maud Land, the Yamato Mountains, Enderby Land or Grove Mountains, Princess Elizabeth Land. They are all located at altitudes between 1900 to 2400 m. This observation might be attributable to the fact that the East Antarctic ice sheet experiences minimal ice stand changes in this altitude range during climate cycles (Delisle 1995), which favours the long-lasting perseverance of ice flow conditions responsible for the build-up of meteorite concentrations.

No meteorite concentration site has previously been detected at these altitudes in the western sector of Queen Maud Land despite the rather similar glaciological situation in comparison to the other sites. One single find in 1961 (the Lazarev meteorite) at the southern rim of the Wohlthat Massiv (Queen Maud Land) provides the first indication for the regional potential for meteorite accumulations. To assess such a potential on blue ice areas south of the Wohlthat Massiv, a reconnaissance survey was carried out by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) of Germany during the Antarctic summer field season 2007/08. The results are presented here.

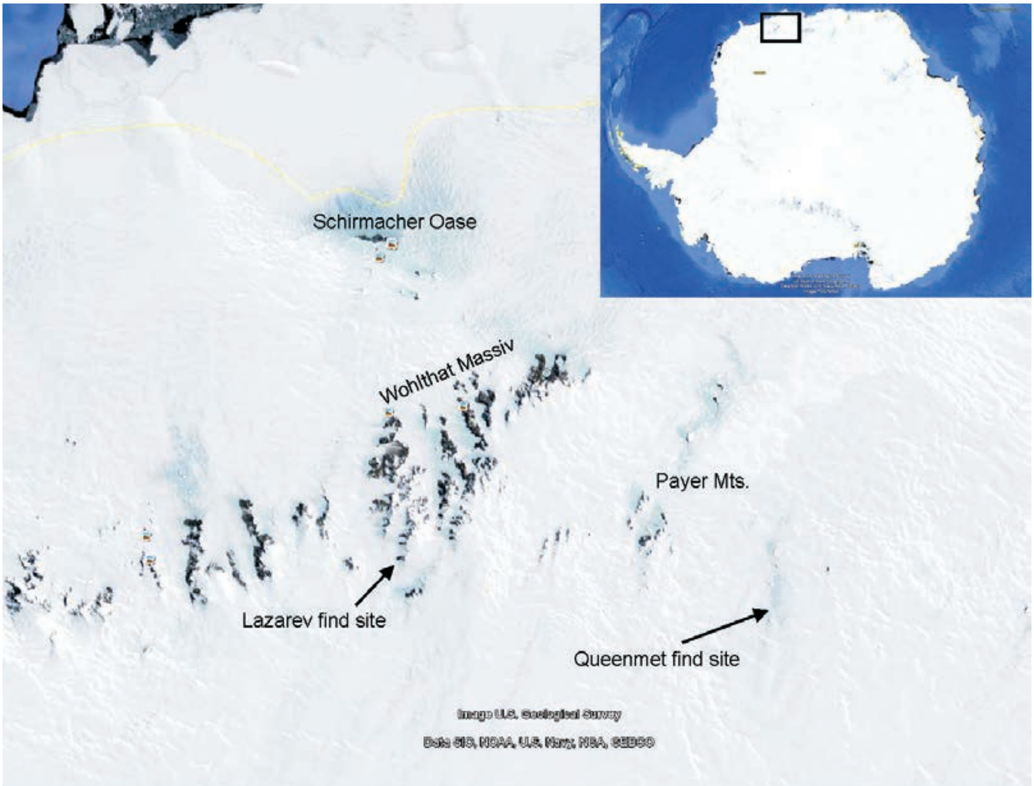

Fig. 1. Geographic overview. The rectangle within inset shows the location of the investigated region. The Steingarden Nunataks find site (Queenmet site) is located on blue ice fields to the SE of the Wohlthat Massiv at a distance of about 160 km from the Lazarev find site. Map data: Google, U.S. Geological Survey, Data SIO, NOAA, Navy, NGA, GEBCO.

Search concept for discovery of meteorite concentration sites

Potential meteorite concentration areas were selected on the basis of three criteria:

- position at an altitude comparable to other Antarctic major meteorite concentrations,
- results of an earlier radar reconnaissance survey in 1995/96 (MEYER *et al.* 2005) which had indicated regions of thin ice cover in the survey area,
- gentle ice surface slope, in conjunction with thin ice cover indicative for slow ice flow.

Based on the study of aerial photographs of blue ice areas within the altitude band between 2000 m and 2500 m, several potential meteorite concentration sites had been identified prior to this expedition. Only one site – the Steingarden Nunataks site – was visited. A second (Payer Mountains area) and third site (Skeidshovden) proved to be inaccessible for the aircraft due to bad weather or unsuitable ice conditions.

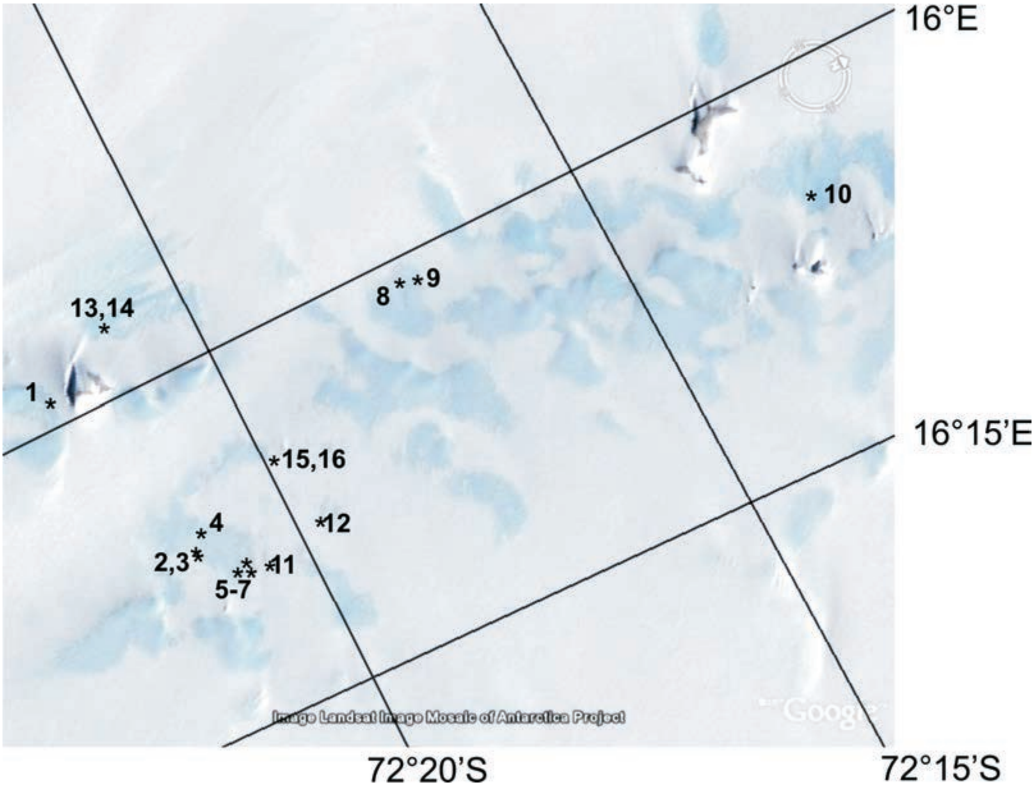

Fig. 2. Location of blue ice fields of the Steingarden Nunataks site and position of recovered meteorites. Numbers indicate sequence of meteorite finds. Map data: Google, Landsat Image Mosaic of Antarctica Project.

The Steingarden nunataks meteorite concentration site

The logistics for access to this site was made possible by the services of the DROMLAN network (a multi-national fleet of aircraft operating to a large part out of the Russian airfield Novolazarevskaya). All the expedition material was flown to and from this site by two DC3-aircrafts of DROMLAN.

Ice flow from the Polar Plateau to the coast is impeded in the survey area by three barriers: the Wohlthat Massiv, the Payer Mountains and a third obstruction to the east, the Queenmet find site (Fig. 1). The latter is characterized by large blue ice fields and the presence of several nunataks, which rise by in general less than 100 m above the ice surface. The ice surface of the Steingarden Nunataks site slopes gently to the northwest in direction to a large ice stream that proceeds from the Polar Plateau between Payer Mountains and the Steingarden Nunataks site toward the coast.

The site itself can be described in general terms to be dominated by a gentle topographic step connecting two unnamed nunataks, which separates ice at a higher elevation to the east in comparison to snow and ice fields to the west. The southern nunatak is located at 72° 23.5′ S, 16° E, the northern one at 72° 13′ S, 16° 8′ E. The ice surface along this topographic step is divided into modest ice depressions and ice rises, presumably indicating hummocky bedrock topography. The presence of numerous patchy blue ice fields is probably caused by sub-ice rises, which is also indicated by the result of one radar survey (MEYER *et al.* 2005) conducted over one visited blue ice field (see below).

As a result of our search campaign 15 meteorites were found at the Steingarden Nunataks site, the majority of them on blue ice on the upper side of a topographic step (see Fig. 2 for find locations) at an elevation of on average 2475 m a.s.l.

The fierce winds blowing over the shoulder of the topographic step remove the snow cover and cause the exposure of blue ice at this site. The distribution of snow and blue ice fields (satellite image was taken in 1999) as shown in Fig. 2 represents only in general terms the blue ice conditions found during the Queenmet-expedition in November 2007. During our visit the extent of the blue ice fields had slightly increased.

Meteorite finds

Seven meteorite find locations (labelled 2–7, 11 in Fig. 2) in the Steingarden Nunataks area are closely spaced and tied to one ice ridge complex, while the rest of the find sites are widely dispersed.

Concentrated find sites: Find sites 2–4 as well as 5–7, 11 are placed on the northern and the latter on the southern face of two ice rises (for more details see Figs 2 and 6). Both ice rises feature also numerous rock fragments on their surface. In particular find sites 5–7 are located on the southern limit of an extended N-S oriented veneer of rock fragments including some m-sized boulders resting on the ice surface. The sub-ice topography of this location is further discussed in section 4.2.

Isolated finds: Find site 1 is unusual as it is located on an ice ramp sloping gently to heavily crevassed terrain. It is, therefore, likely that the meteorite in question (STG 07001) had rested only for a short time on the surface of this ice field. The find sites 8 and 9 – downstream of the major concentration site – are located on the western shoulder of an elongated S-N trending ice depression, which during our visit was largely covered by snow (see also Fig. 3). A 31 kg iron meteorite was recovered at find site 9. The find site 10 is located at the southern end of an extended, SE-NW oriented moraine being exposed on the surface of an ice depression between two nunataks. An isolated find at the edge of a large blue ice field was made on blue ice at find site 12. Find sites 13 and 14, only about 100 m apart, were located on an elongated minor ice rise in front of a nunatak and featured two meteorites, very fresh in appearance. Both objects originate obviously from the same fall, because the fracture surfaces of both fragments match perfectly. Find sites 15 and 16 are near an ice rise loosely covered with rock fragments.

Fig. 3. General view of the find site (arrow) of the 31 kg iron meteorite.

Table 1 gives details for coordinates, weight and classification for all stony meteorites found in the area. The meteorites received the official name “Steingarden Nunataks” (STG) from the Meteoritical Society Nomenclature Committee (Meteoritical Bulletin 102).

In comparison to other search campaigns for Antarctic meteorites, the average weight (49.6 g) of the meteorites recovered by the Queenmet expedition (with the iron meteorite disregarded because of its unusual weight) is rather large. In other words, we apparently have largely missed the so called wind-blown portion of the regional meteorite concentration, which would be represented primarily by the <10 g-fraction. The weight distribution of our collection is shown in Fig. 4. The snow ice interface at the downwind side of the investigated area did not yield a single find. A possible explanation for this missing portion might be that the interface area mostly coincides with heavily crevassed terrain. The frequent very high wind speeds in the investigated area, which is fully exposed to the katabatic winds from the Polar Plateau, probably represent a second unfavourable factor for the build-up of a wind-blown meteorite concentration. The removal rate of small meteorites is most likely very high. During our stay, only about 30 % of the available time was suitable for field work due to adverse wind conditions.

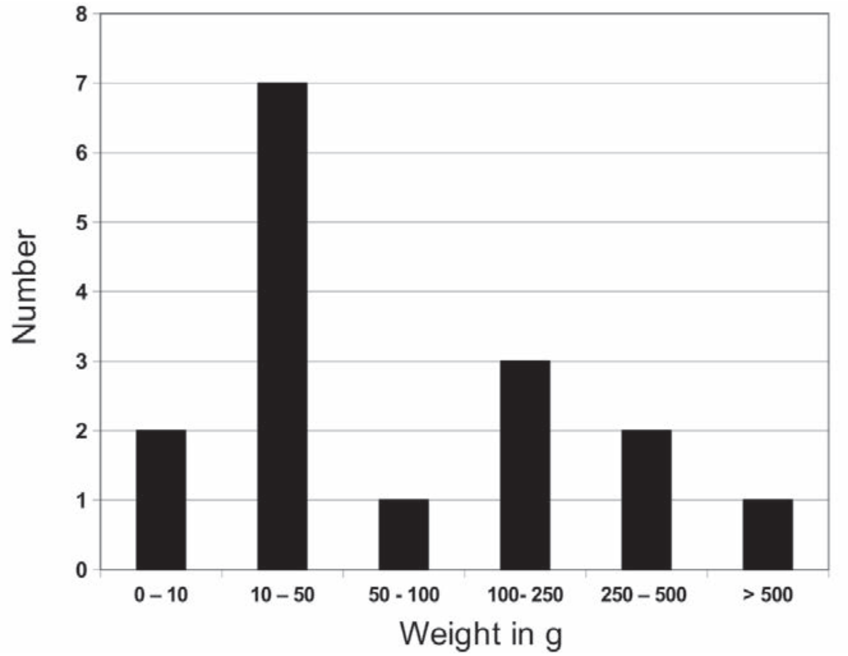

Fig. 4. Weight distribution for all meteorites recovered by the Queenmet expedition. Notable is the near absence of the low mass (the wind-blown) fraction.

Table 1. Classification of all stony meteorites found by the Queenmet-expedition in 2007 in the vicinity of the Steingarden Nunataks (STG) site.

Name	weight (g)	Longitude (E)	Latitude (S)	class	shock stage	weathering grade
STG 07001	454.8	15° 59.394'	72° 21.98'	L6	6	W1
STG 07002	21.9	16° 06.621'	72° 21.06'	L6	3	W1
STG 07003	11.9	16° 06.705'	72° 21.104'	L6	3	W1
STG 07004	17.6	16° 06.749'	72° 21.095'	L6	3	W1
STG 07005	83.3	16° 08.938'	72° 20.842'	H4	3	W1
STG 07006	287.8	16° 08.537'	72° 20.901'	L5	3	W1
STG 07007	112.3	16° 08.94'	72° 20.866'	H5/6	1	W1-W2
STG 07008	225.1	16° 02.14'	72° 17.458'	H4	3	W1
STG 07010	21.9	16° 06.318'	72° 12.595'	H6	1	W0
STG 07011	15.4	16° 09.565'	72° 20.64'	LL4/5	3	W2
STG 07012	11.4	16° 08.584'	72° 19.536'	L5/6	3	W0-W1
STG 07013	188.6	15° 57.954'	72° 20.883'	H5	1	W0-W1
STG 07015	5.1	16° 05.266'	72° 19.849'	L6	3	W1
STG 07016	1.9	16° 05.266'	72° 19.849'	L6	3	W1

Meteorite classification

The meteorites were classified jointly by F. B. and C. K. Type specimens are kept at the Natural History Museum, Vienna. Main masses are stored at the BGR, Hannover. All meteorites – except the 31 kg iron mass- are ordinary chondrites. Some key parameters for the stony meteorites are listed in Table 1. Assignments of meteorite class, shock stage, and weathering grade are based on the classification schemes of Van Schmus & Wood (1967), Stöffler *et al.* (1991) and Wlotzka (1993), respectively. The classification of the recovered iron meteorite (un-official name STG 07009) is not yet completed and will be published elsewhere.

Methods

For the mineralogical investigation of the Steingarden Nunataks chondrites polished thin sections were prepared. Petrographic characterization was performed by using optical microscopy and analytical scanning microscopy (SEM Jeol JSM-6400). Mineral analyses were carried out with an ARL-SEMQ electron microprobe at 15 kV accelerating voltage and 15 nA sample current (on benitoite). The bulk chemical compositions of the meteorites were obtained by instrumental neutron activation analysis (INAA) at the University of Vienna; for details of this method see Mader & Koeberl (2009). Bulk chemical compositions for 26 selected major and trace elements of all chondritic STG meteorites are given in Table 2.

Brief description of the classified chondrites

STG 07001

Macroscopic description: Brown stone partly covered by black fusion crust. Cut surfaces exhibit thin (< 2 mm) shock veins and in places moderate cracks. A few chondrule outlines and finely dispersed metal grains are visible. The interior is grey with rusty areas around metal particles.

Microscopy: The meteorite exhibits a strongly recrystallized texture and appears strongly shocked. Irregular distributed thin shock veins cross-cut the whole section. Well-defined chondrules are absent and only a few relic chondrules are present. The apparent diameter of “plagioclase” which is completely transformed into maskelynite exceeds in places 100 µm. In areas adjacent to melt veins some olivine grains show recrystallization textures. Weathering effects are limonitic staining, minor oxide rims around metal and minor oxide veins.

Mean composition of olivine and low-Ca pyroxene: Fa = 25.2 $\pm$ 0.3; Fs = 21.6 $\pm$ 0.3; Wo = 1.5 $\pm$ 0.2

Classification: L6 chondrite, shock stage S6, weathering grade W1

Table 2. Selected major and trace element abundances of Steingarden Nunataks meteorites, obtained by instrumental neutron activation analysis. All data in ppm, except as noted.

STG	07001	07002	07003	07004	07005	07006	07007	07008	07010	07011	07012	07013	07015
	L6	L6	L6	L6	H4	L5	H5/6	H4	H6	LL4/5	L5/6	H5	L6
Na	7655	4900	6838	6679	6388	6223	6143	6870	6385	8102	6852	5945	7536
Sc	9.09	7.62	8.52	9.80	8.41	7.97	7.26	8.41	8.14	8.78	8.33	7.92	7.80
Cr	3774	3872	3702	3357	3707	3292	3317	3546	3530	3972	3604	3294	3982
Fe (wt%)	21.9	23.4	17.5	18.2	23.9	23.3	26.8	27.1	26.2	18.6	23.1	27.1	22.8
Co	463	462	389	429	558	797	823	802	802	531	704	835	814
Ni (wt%)	12248	14066	7413	9759	12641	15919	16063	17490	18144	10628	13963	15755	13253
Zn	57	34	35	35	38	43	48	44	42	45	51	70	44
Ga	6	<20	3	4	5	5	5	<10	5	3	5	5	4
As	1.41	2.04	0.94	1.24	0.95	2.21	2.52	2.99	2.21	1.49	2.23	2.44	1.31
Se	6.7	12.6	3.6	3.9	7.2	6.0	5.6	4.5	4.1	4.1	5.9	5.1	4.7
Br	0.3	<0.4	0.4	0.4	0.3	0.3	0.6	<0.4	0.4	1.1	0.4	0.3	0.3
Zr	9	<12	9	<13	<10	<20	<10	<13	<15	<15	<18	<13	9
Sb	0.07	0.06	0.07	0.06	0.07	0.08	0.07	0.08	0.1	0.07	0.08	0.06	0.08
Cs	0.05	<0.1	<0.1	0.06	0.07	<0.1	0.05	<0.1	<0.1	0.1	<0.2	<0.2	<0.2
Ba	3.1	<6	4	3.5	<20	4	3.8	<20	<25	<20	4	3	<10
La	0.29	<0.2	0.17	<0.2	0.37	0.29	0.30	0.22	0.42	0.48	0.12	0.32	0.31
Ce	0.95	<1	0.85	<1	1.06	1.1	1.04	0.96	1.20	1.73	0.80	1.26	1.06
Sm	0.20	0.22	0.18	0.19	0.21	0.19	0.21	0.21	0.22	0.31	0.11	0.31	0.23
Eu	0.10	0.07	0.06	0.05	0.08	0.07	0.07	0.07	0.08	0.10	0.05	0.10	0.09
Gd	<0.3	<0.3	<0.3	<0.4	0.28	0.3	0.32	0.3	0.28	0.4	<0.3	0.5	<0.3
Yb	0.18	0.22	0.18	0.16	0.19	0.21	0.24	0.22	0.18	0.31	0.18	0.38	0.24
Lu	0.04	0.04	0.03	0.03	0.03	0.04	0.05	0.05	0.04	0.07	0.03	0.08	0.05
Hf	0.14	0.10	0.11	0.09	0.13	0.11	0.13	<0.15	<0.2	0.15	0.14	0.12	0.11
Os	0.6	0.5	0.3	0.2	0.8	0.5	0.8	0.8	0.7	0.4	0.6	0.9	0.4
Ir (ppb)	448	359	333	418	658	470	664	724	711	433	472	728	497
Au (ppb)	253	207	133	166	242	283	333	332	311	164	277	329	247

STG 07002

Macroscopic description: Almost fully encrusted stone with a dull black fusion crust. The cut surface exhibits a greyish interior with finely dispersed metal grains and an apparent lack of chondrules. In places, the matrix contains very thin (<< 1 mm) shock veins and minor rusty areas.

Microscopy: The meteorite exhibits a strongly recrystallized texture. Chondrule outlines are completely absent. The apparent diameter of plagioclase exceeds in places 100 µm and some of the larger feldspar grains exhibit polysynthetic twinning. Shock metamorphic features comprise undulatory extinction of olivine, pyroxene, plagioclase, and the presence of planar fractures in olivine. Weathering effects are limonitic staining, rare oxide rims around metal and very few oxide veins.

Mean composition of olivine and low-Ca pyroxene: Fa = 22.7 $\pm$ 0.4; Fs = 19.4 $\pm$ 0.3; Wo = 3.8 $\pm$ 0.3

Classification: L6 chondrite, shock stage S3, weathering grade W1

STG 07003

Macroscopic description: Almost fully encrusted stone with a dull black fusion crust. The cut surface exhibits a greyish interior with finely dispersed metal grains and minor staining. Chondrule outlines are absent.

Microscopy: The overall microscopic features are very similar to those of STG 07002.

Mean composition olivine and low-Ca pyroxene: Fa = 22.7 $\pm$ 0.3; Fs = 18.7 $\pm$ 0.4; Wo = 4.1 $\pm$ 0.2

Classification: L6 chondrite, shock stage S3, weathering grade W1

STG 07004

Macroscopic description: Almost fully encrusted stone with a dull black fusion crust and regmaglypts. The interior consists of a greyish matrix with finely dispersed metal grains and minor staining. Chondrule outlines are absent.

Microscopy: The overall microscopic features are very similar to those of STG 07002.

Mean composition olivine and low-Ca pyroxene: Fa = 22.6 $\pm$ 0.2; Fs = 19.1 $\pm$ 0.3; Wo = 3.7 $\pm$ 0.5

Classification: L6 chondrite, shock stage S3, weathering grade W1

STG 07005

Macroscopic description: Dark brown stone partly covered by fusion crust that fell apart along cracks. Cut surfaces reveal a dark-grey metal-rich interior with minor oxidation. Rusty areas are confined to cracks.

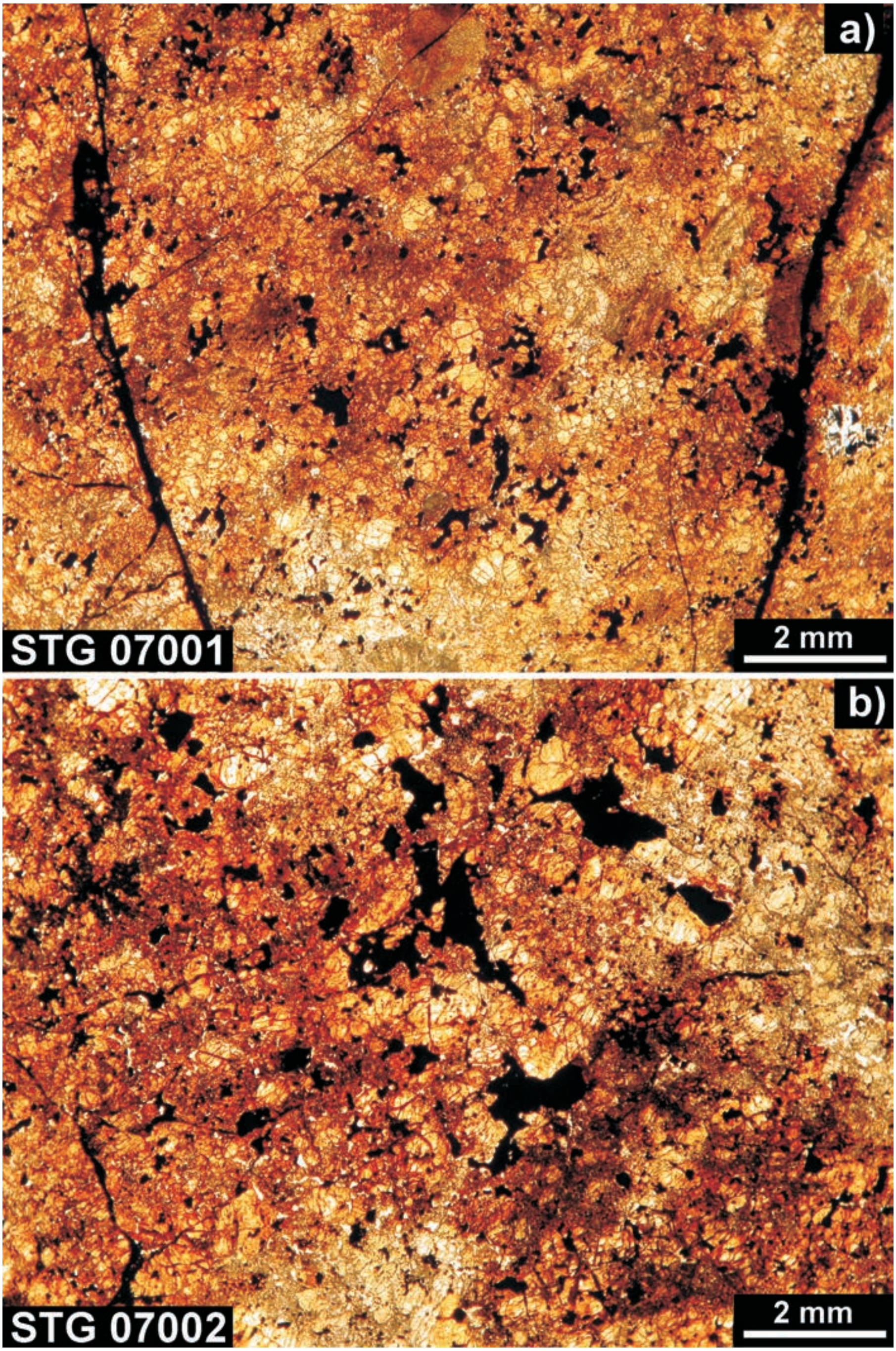

Fig. 5. Photomicrographs (plain polarized light) exhibiting the characteristic textures of the Steingarden Nunataks meteorites STG 07001 (a), STG 07002 (b), STG 07003 (c), STG 07004 (d), STG 07005 (e), STG 07006 (f), STG 07007 (g), STG 07008 (h), STG 07010 (i), STG 07011 (j), STG 07012 (k) STG 07013 (l), STG 07015 (m), and STG 07016 (n).

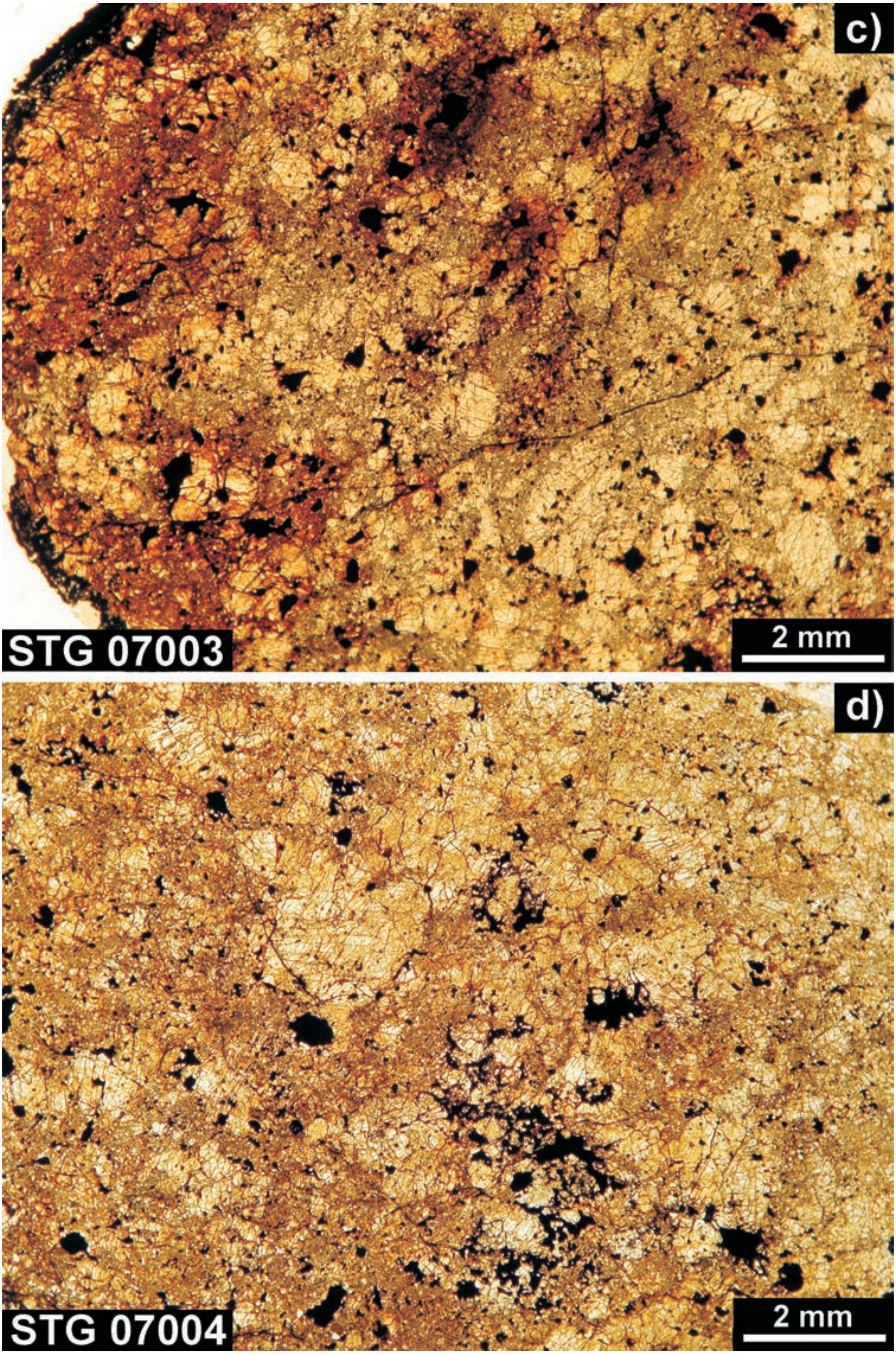

Fig. 5c–d

Microscopy: The thin section shows chondrules (up to ~ 1.5 mm) with well-defined boundaries set into a recrystallized matrix. Some chondrules consisting of devitrified glass exhibit feathery textures. Twinned clinopyroxene grains are common. Shock metamorphic features comprising undulatory extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Weathering effects are limonitic staining, minor oxide rims around metal and minor oxide veins.

Mean composition of olivine and low-Ca pyroxene: Fa = 18.6 $\pm$ 0.2; Fs = 16.5 $\pm$ 0.3; Wo = 0.8 $\pm$ 0.2

Classification: H4 chondrite, shock stage S3, weathering grade W1

STG 07006

Macroscopic description: Almost fully encrusted stone that fell apart along oxidized cracks. Cut surfaces reveal a light-grey interior with finely dispersed metal grains and significant staining along fractures. In places, dark-grey chondrules are visible.

Microscopy: The thin section shows not well-delineated but clearly discernible chondrules (up to ~ 1.5 mm) set into a recrystallized matrix. Twinned clinopyroxene is absent. Shock metamorphic features comprising undulatory extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Weathering effects are limonitic staining, minor oxide rims around metal and minor oxide veins.

Mean composition of olivine and low-Ca pyroxene: Fa = 24.5 $\pm$ 0.2; Fs = 20.9 $\pm$ 0.4; Wo = 1.3 $\pm$ 0.2

Classification: L5 chondrite, shock stage S3, weathering grade W1

STG 07007

Macroscopic description: Dark-brown stone partly covered by black fusion crust. The cut surface exhibits a fine-grained grey interior consisting of an in places metal-rich and porous matrix. A few chondrule outlines are clearly visible.

Microscopy: The thin section shows not well-delineated but clearly discernible chondrules (up to ~ 2 mm). In places, chondrule outlines are indistinct in the recrystallized matrix. Twinned clinopyroxene is absent. Sharp optical extinction of olivine indicates that the meteorite is unshocked. In reflected light pores (up to 0.2 mm) partly filled by weathering oxides are visible. However, most of the metal grains are unaffected by oxidation.

Mean composition olivine and low-Ca pyroxene: Fa = 18.3 $\pm$ 0.1; Fs = 16.6 $\pm$ 0.1; Wo = 1.5 $\pm$ 0.2

Classification: H5/6 chondrite, shock stage S1, weathering grade W1–W2

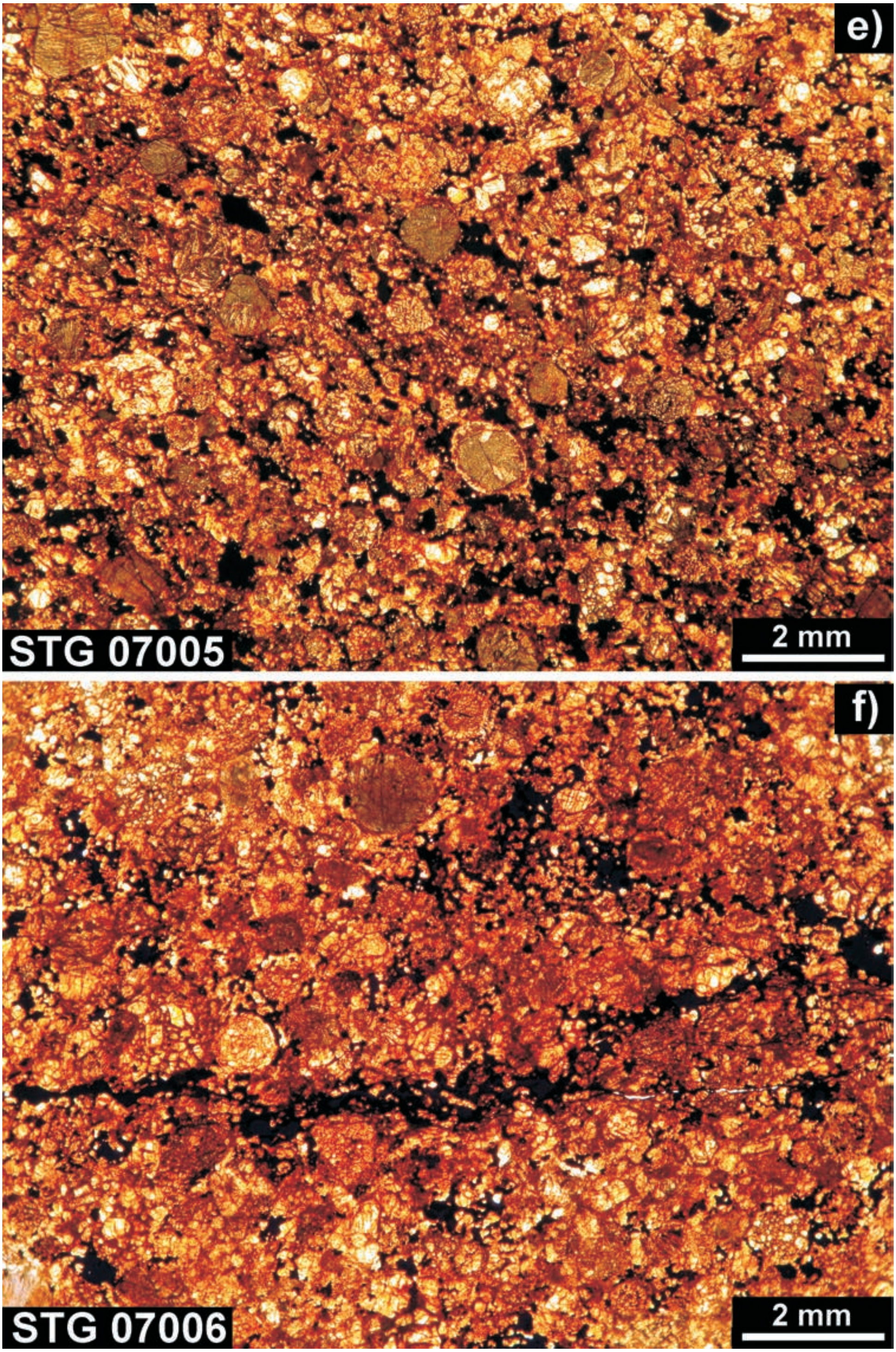

Fig. 5e–f

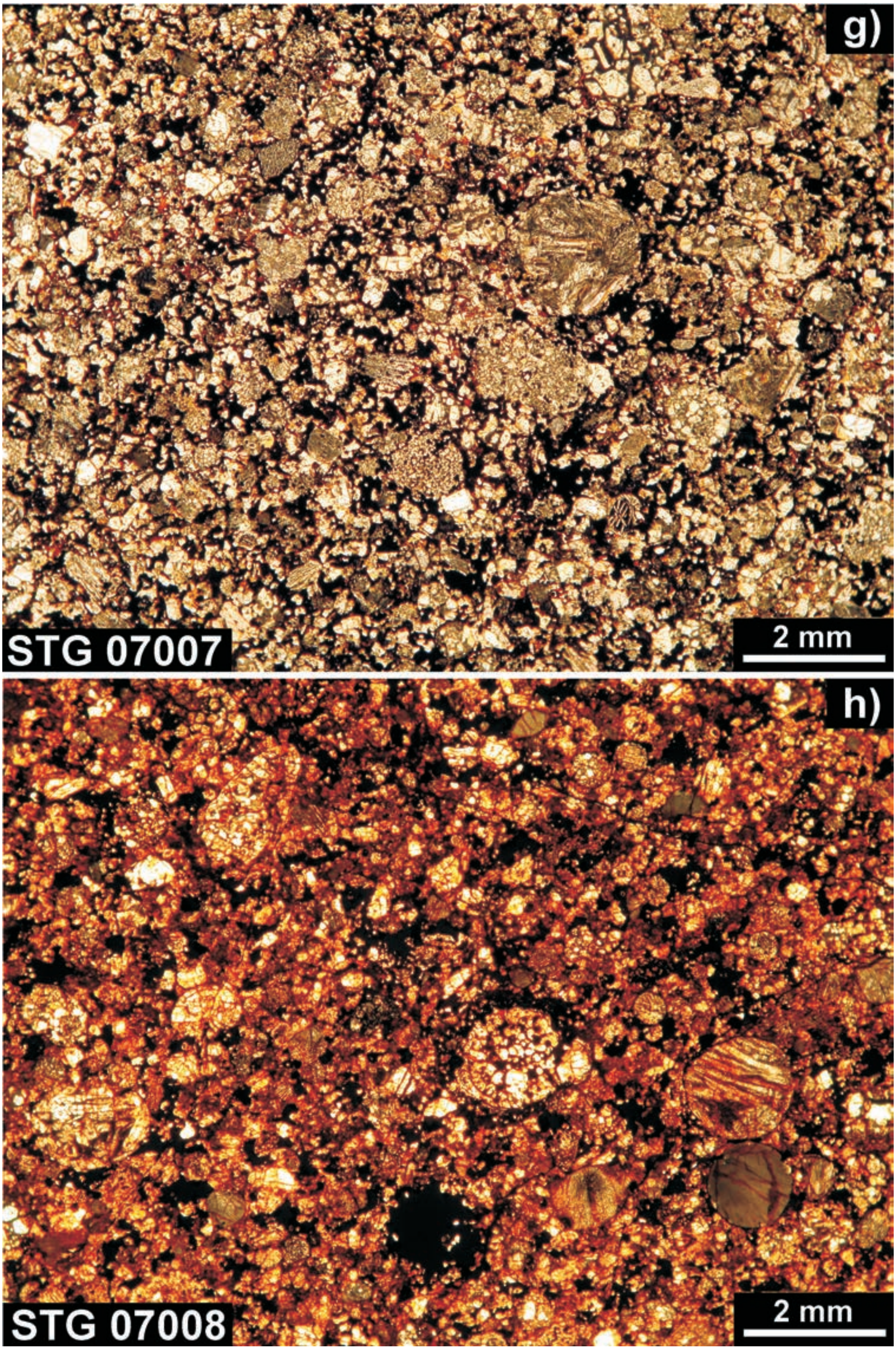

Fig. 5g–h

STG 07008

Macroscopic description: Dark brown stone partly covered by black fusion crust. The cut surface exhibits a greyish-brown interior with numerous finely dispersed metal grains. In places, well-defined chondrules are visible.

Microscopy: The thin section shows chondrules (up to ~ 2 mm) with well-defined boundaries set into a recrystallized matrix. In places, the chondrule mesostasis consists of very fine-grained recrystallized glass. Grains of twinned clinopyroxene are common. Shock metamorphic features comprising undulatory extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Despite intense limonitic staining, weathering is restricted to minor oxide rims around metal and minor oxide veins.

Mean composition of olivine and low-Ca pyroxene: $Fa = 18.9 \pm 0.3$; $Fs = 16.3 \pm 0.2$; $Wo = 0.8 \pm 0.1$

Classification: H4 chondrite, shock stage S3, weathering grade W1

STG 07010

Macroscopic description: Stone, partly covered by a thick fractured black fusion crust. The fine-grained gray matrix exposed on a cut surface is metal-rich with only minor staining along cracks. Chondrules are not visible.

Microscopy: The meteorite exhibits a strongly recrystallized texture. Chondrules exhibiting well-delineated outlines are lacking and only a few relic chondrules are present. Twinned clinopyroxene is absent. The apparent diameter of plagioclase crystals is > 50 µm. Sharp optical extinction of olivine indicates that the meteorite is unshocked. Weathering effects are restricted to minor limonitic staining.

Mean composition of olivine and low-Ca pyroxene: $Fa = 19.1 \pm 0.1$; $Fs = 17.2 \pm 0.2$; $Wo = 1.2 \pm 0.2$

Classification: H6 chondrite, shock stage S1, weathering grade W0

STG 07011

Macroscopic description: Stone, partly covered by a dull black fusion crust. Cut surfaces exhibit a light grey interior with very few finely dispersed metal grains. Numerous small (~ 1 mm in diameter) chondrules are visible on both – the broken and cut surfaces.

Microscopy: The thin section shows mainly well-defined chondrules (up to ~ 2 mm). In places, some chondrule outlines are discernable but not clearly distinct from in the recrystallized matrix. Twinned clinopyroxene is rare. The apparent diameter of plagioclase crystals is < 20 µm. Shock metamorphic features comprising undulatory

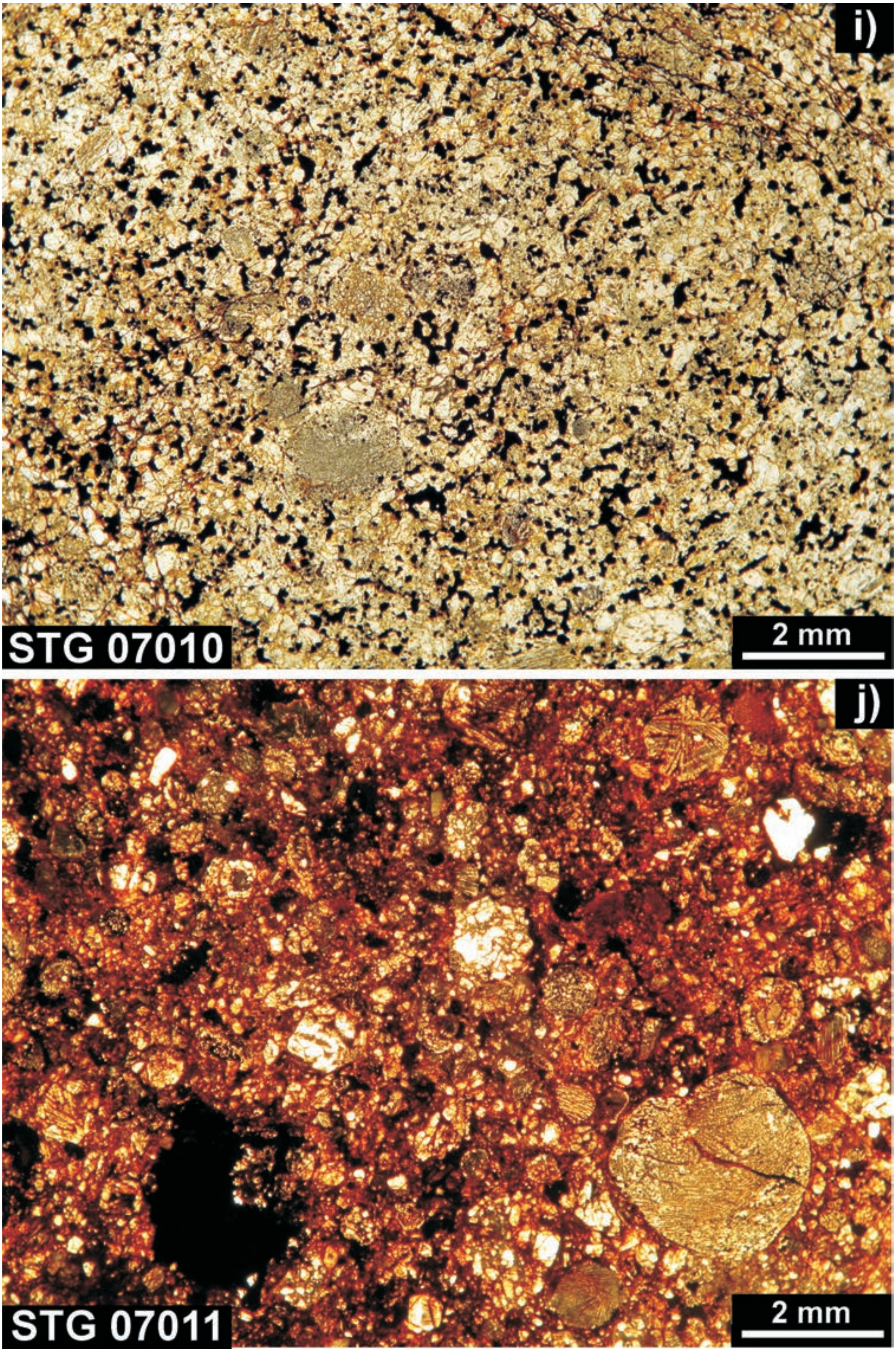

Fig. 5i–j

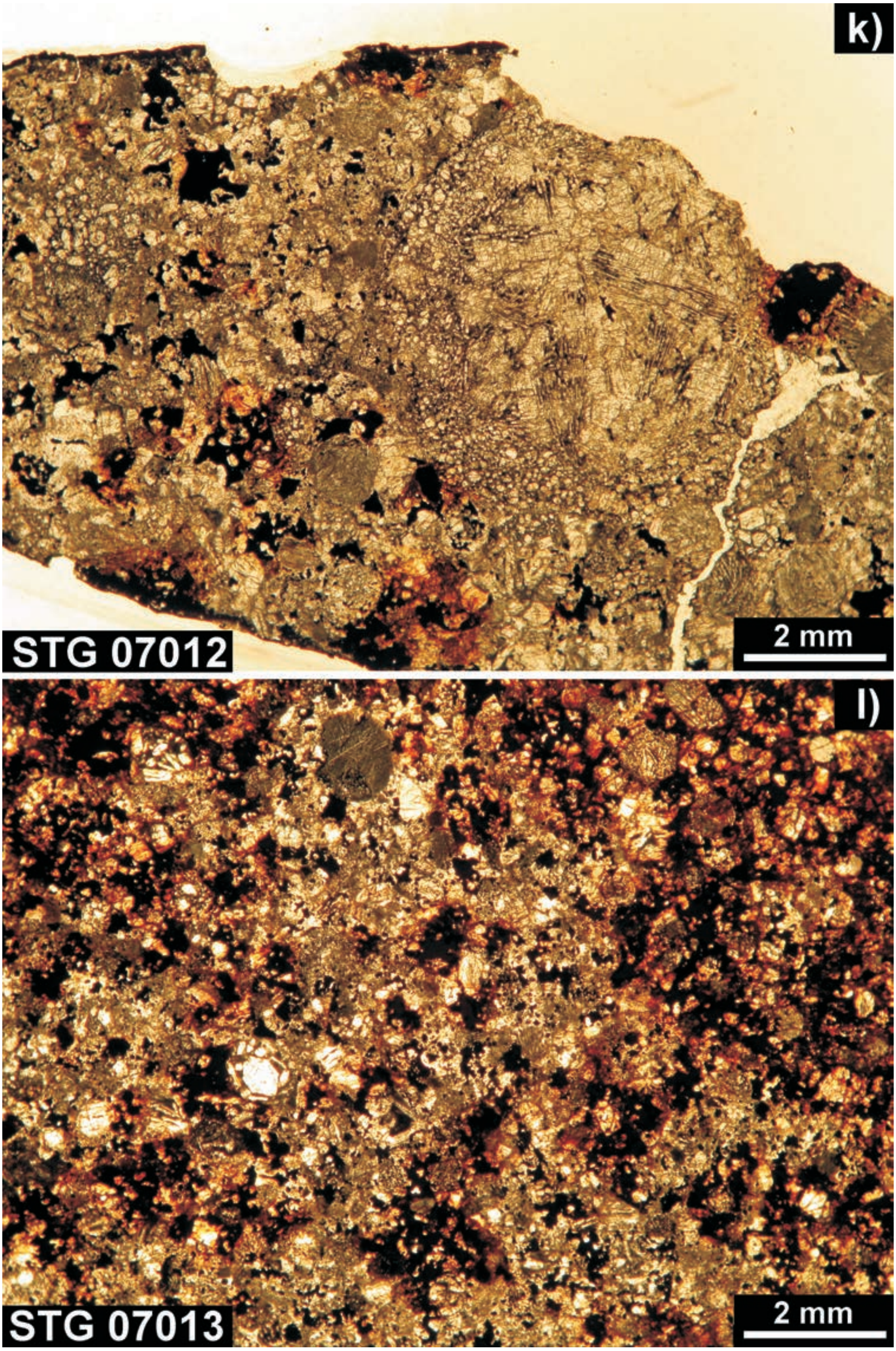

Fig. 5k–l

extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Weathering effects comprise intense limonitic staining and significant oxidation of metal (about 50 % affected).

Mean composition of olivine and low-Ca pyroxene: Fa = 29.5 $\pm$ 0.5; Fs = 23.8 $\pm$ 0.5; Wo = 1.0 $\pm$ 0.2

Classification: LL 4/5 chondrite, shock stage S3, weathering grade W2

STG 07012

Macroscopic description: Stone, partly covered by a black fusion crust with some minor oxidation around metal grains. A cut surface reveals the fresh-looking light-grey interior with some dispersed metal flakes and in places well-defined chondrule outlines.

Microscopy: The thin section shows not well-delineated but clearly discernible chondrules (up to ~ 6 mm). In places, chondrule outlines are indistinct in the recrystallized matrix. Twinned clinopyroxene is absent. The apparent diameter of plagioclase crystals is < 50 µm. Shock metamorphic features comprising undulatory extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Weathering effects are limonitic staining and very rare oxide rims around metal grains.

Mean composition of olivine and low-Ca pyroxene: Fa = 22.7 $\pm$ 0.4; Fs = 20.0 $\pm$ 0.5; Wo = 1.6 $\pm$ 0.1

Classification: L5/6 chondrite, shock stage S3, weathering grade W0–W1

STG 07013

Macroscopic description: One stone consisting of two fragments found about 50 m apart. The individual pieces are covered by a dull black fusion crust and have dark-brown weathered natural broken surfaces that match perfectly. The dark-grey interior is metal-rich and exhibits numerous well-defined chondrules.

Microscopy: The meteorite shows not well-delineated but clearly discernible chondrules (up to ~ 1.3 mm) set into a recrystallized matrix. Twinned clinopyroxene is absent. The apparent diameter of plagioclase crystals is < 50 µm. Sharp optical extinction of olivine indicates that the meteorite is unshocked. Weathering effects are limonitic staining, minor oxide rims around metal and minor oxide veins.

Mean composition olivine and low-Ca pyroxene: Fa = 18.3 $\pm$ 0.1; Fs = 16.7 $\pm$ 0.3; Wo = 1.7 $\pm$ 0.1

Classification: H5 chondrite, shock stage S1, weathering grade W1

STG 07015

Macroscopic description: Small stone covered by a thick black fusion crust. The light-grey interior exposed on a broken surface is in places rusty and exhibits some dispersed metal/sulfide grains. Chondrules are not visible.

Microscopy: The meteorite exhibits a strongly recrystallized texture. Well-defined chondrules are lacking and only a few relic chondrules are discernible. Twinned clino-pyroxene is absent. The apparent diameter of plagioclase crystals is > 50 µm. Shock metamorphic features comprising undulatory extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Weathering effects are intense limonitic staining, minor oxide rims around metal and minor oxide veins.

Mean composition olivine and low-Ca pyroxene: Fa = 28.4 $\pm$ 0.4; Fs = 21.3 $\pm$ 0.2; Wo = 1.5 $\pm$ 0.1

Classification: L6 chondrite, shock stage S3, weathering grade W1

STG 07016

Macroscopic description: Small fully encrusted stone with a black fusion crust. The cut surface exhibits a few metal flakes and has minor rust. Chondrules are not visible.

Microscopy: The meteorite exhibits a strongly recrystallized texture. Well-defined chondrules are lacking and only a few relic chondrules are discernible. Twinned clino-pyroxene is absent. The apparent diameter of plagioclase crystals is > 50 µm. Undulatory extinction of olivine and pyroxene, and the presence of planar fractures in olivine indicate that the meteorite is weakly shocked. Despite intense limonitic staining, oxide rims around metal and oxide veins are present in minor quantities.

Mean composition olivine and low-Ca pyroxene: Fa = 24.7 $\pm$ 0.5; Fs = 20.9 $\pm$ 0.4; Wo = 1.7 $\pm$ 0.2

Classification: L6 chondrite, shock stage S3, weathering grade W1

Ice thickness measurements with ground-based radar

The airborne radar survey of the region by BGR in 1995 with widely spaced profiles (Meyer *et al.* 2005) had marginally touched the Steingarden nunataks site. The one available line touching the western portion of the Steingarden nunataks site indicates a range of ice thickness between 0–1000 m.

One ground based radar profile connecting two principal meteorite find sites (find points 2–4 and 5–7; Fig. 2) was carried out by Queenmet. Both find sites rest on ice raises, separated by a shallow ice depression (Fig. 6). Ten point measurements distributed over a distance of 2.8 km did reveal a sub-ice glacial valley with a maximum ice thickness of

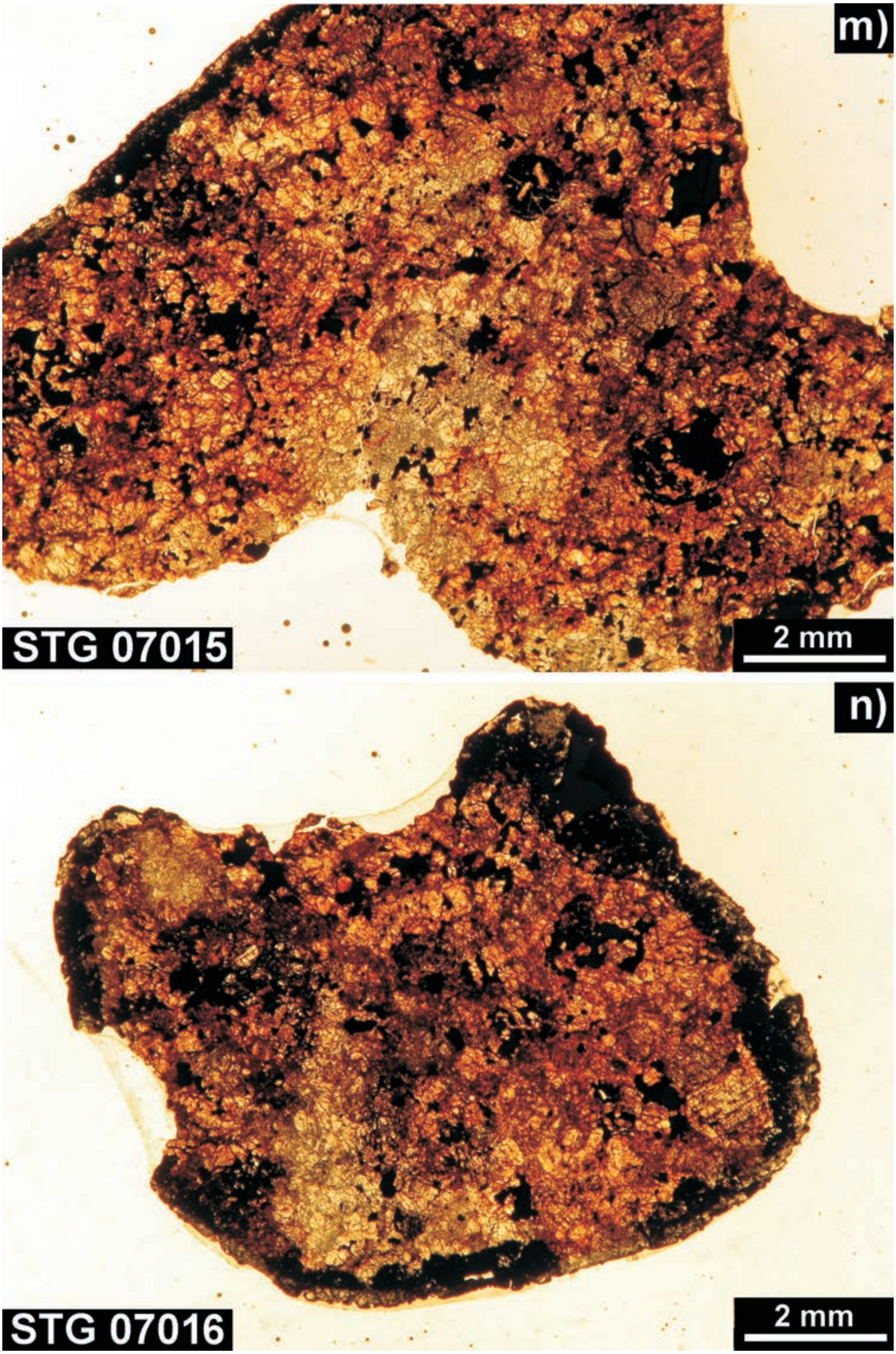

Fig. 5m–n

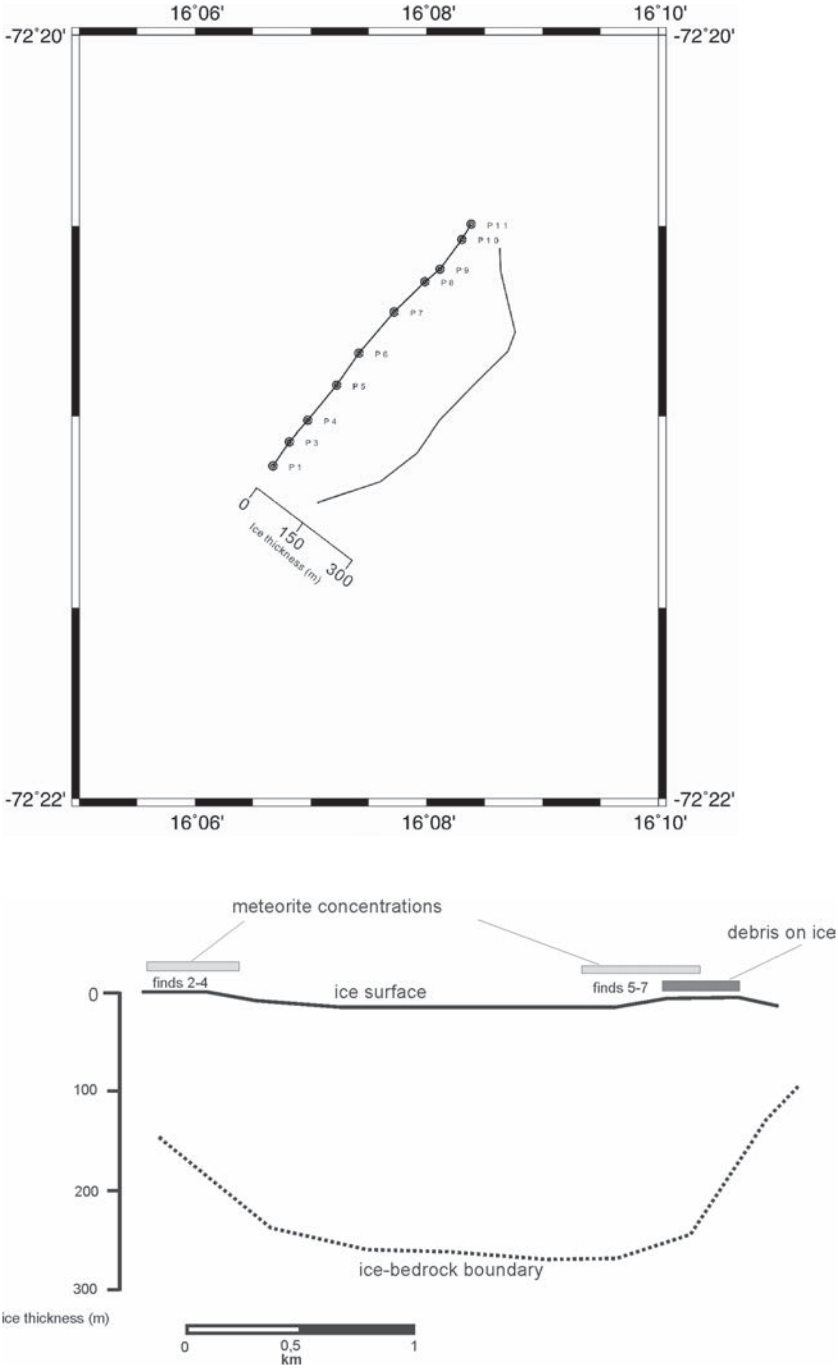

Fig. 6. Location of radar profile and points of measurements (dots) between two major find sites (top) and meteorite concentrations and debris veneer concentrate on the shoulders of a 269 m deep (maximum) glacial valley (bottom) .

269 m. The measurements were done with a BGR-built radar instrument (more details in DELISLE & SIEVERS 1991), especially designed for analysis of ice (or salt) layers.

These values taken together with a regional ice slope of about 1 m/100 m are indicative of ice flow velocities in the order of less than 1 m/year.

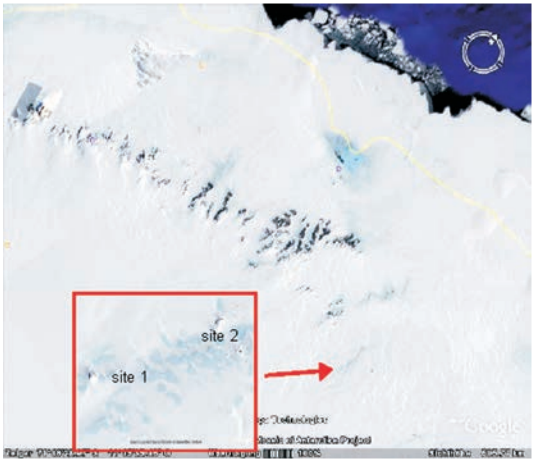

Fig. 7. Position of the Steingarden Nunataks site. The red arrow points at the location which is shown in more detail by the inset. Rock samples were collected at site 1 and site 2 from one nunatak each. Map data: Google, Landsat Image Mosaic of Antarctica Project.

Rock exposure dating of the Steingarden nunataks find site

The result of an extensive survey of rock exposure ages for the Wohlthat Massiv (ALTMAIER *et al.* 2010) – an area about 160 km to the northwest of the Steingarden nunataks site – implies for the last million of years either a modest reduction of ice levels or slow rise of the mountains over the ice shield or a combination of both factors. Apparently only minor changes of the ice level (on the order of few tens of meters) did occur even during the course of climatic changes (cold-warm stages). This scenario favours the long-term stability of meteorite concentrations, wherever they develop in the area. In this context suitable rock samples from bedrock for rock exposure dating were collected from two nunataks (sites 1 and 2 in Fig. 7) bounding at the Steingarden nunataks site to gain further insight into the glaciological long-term evolution of the area.

A detailed discussion of the analysis of the collected samples will be presented elsewhere (STRUB *et al.*, submitted). The results imply the emergence of the top of the nunatak in area 1 (peak altitude is 2652 m) 3 to 4 My ago and of the tops of the nunataks in area 2 (peak altitude = 2368 m) 0.65 to 1.1 My ago. Today the tops of these nunataks have risen about 100 m over the current ice surface. These results concur with the earlier findings by ALTMAIER *et al.* (2010) and suggest glaciological suitable conditions for the buildup of meteorite concentrations at least for the last 10^5 years.

Blue ice areas in the vicinity of the Steingarden nunataks site

A variety of blue ice fields exist to along the 2200 m elevation line of Queen Maud Land. Several of these fields can be excluded to possess high meteorite concentrations. Available radar data show them to cover thick ice and or to possess fairly steep slopes. Both factors point to rather high ice flow velocities which would be an unfavourable condition for build-up of any meteorite concentration. There are two potential sites which we have analysed in greater detail: Payer Mountains and the Lazarev find site.

The Payer Mountains site

A search for meteorites at this site had been organized by a team of the Indian Antarctic Program in 1991, but no meteorites were found. The glaciological situation at this site – based on the evidence of aerial photographs – appears in principle favourable for the build-up of meteorite concentrations. Our plan to land there by aircraft was thwarted due to three reasons: a) bad weather conditions, b) the chosen favoured snow-ice runway turned out to be laterally too inclined and c) the remaining blue ice surfaces were too littered with rock fragments. It was noted from the plane that the blue ice along the north-western face of the Payer Mountains is considerably crevassed which is an unfavourable precondition for the build-up of a meteorite concentration. Any existing meteorite concentration in this area will probably only be found on blue ice in the central portion of the Payer Mountains.

The Lazarev-site

An iron meteorite was found by the 6th Soviet Antarctic expedition in 1961 during a geological study of the southern ridges of the Humboldt Mountains in the central part of Queen Maud Land. According to Ravich & Revnov (1968), the meteorite (consisting of 2 fragments weighing about 7 kg and 3 kg) was found "*on the gentle part of a steep slope of an isolated mountain…*" at the position 71°57′ S, 11°31′ E. A description by the Museum of Extraterrestrial Material of the Russian Academy of Sciences – see: http://www.geokhi.ru/~meteorit/opis/lazarev-e.html) – offers a different site description – "*meteorite covered by chips of sandstone*" – which, however, does not fit the regional/ local geology. Rocks exposed near/at position 71°57′ S, 11°31′ E consist of metaplutonic and metavolcanic sequences (Paech *et al.* 2005). Sedimentary rocks are not exposed in the Humboldt Mountains. The site description given in the Meteorite Catalogue of the British Museum (Grady 2000), based on Buchwald (1975) describes the find site as follows: "*…were found 3000 m above sea-level on a southern spur of the Humboldt Mountains, 35 to 40 m from the fringe of the glacial sheet.*" The elevation is clearly erroneous – the true elevation of the site (based on the given coordinates) is closer to 2500 m. All regional rock exposures and the regional ice level are below 3000 m. The available translation of the field book of Ravich (1995) specifically attributes the Lazarev find to the "observation point 811". The geologic description of observation point 811 mentions melanocratic diorite-syenites as the main mass of the outcrop, a description, which does not concur with the presence of metaplutonic/ metavolcanic sequences at the site with the given coordinates. The description fits, however, closely the geologic description of an isolated mountain nearby, which was identified to consist of monzonite-syenites (Paech *et al.* 2005).

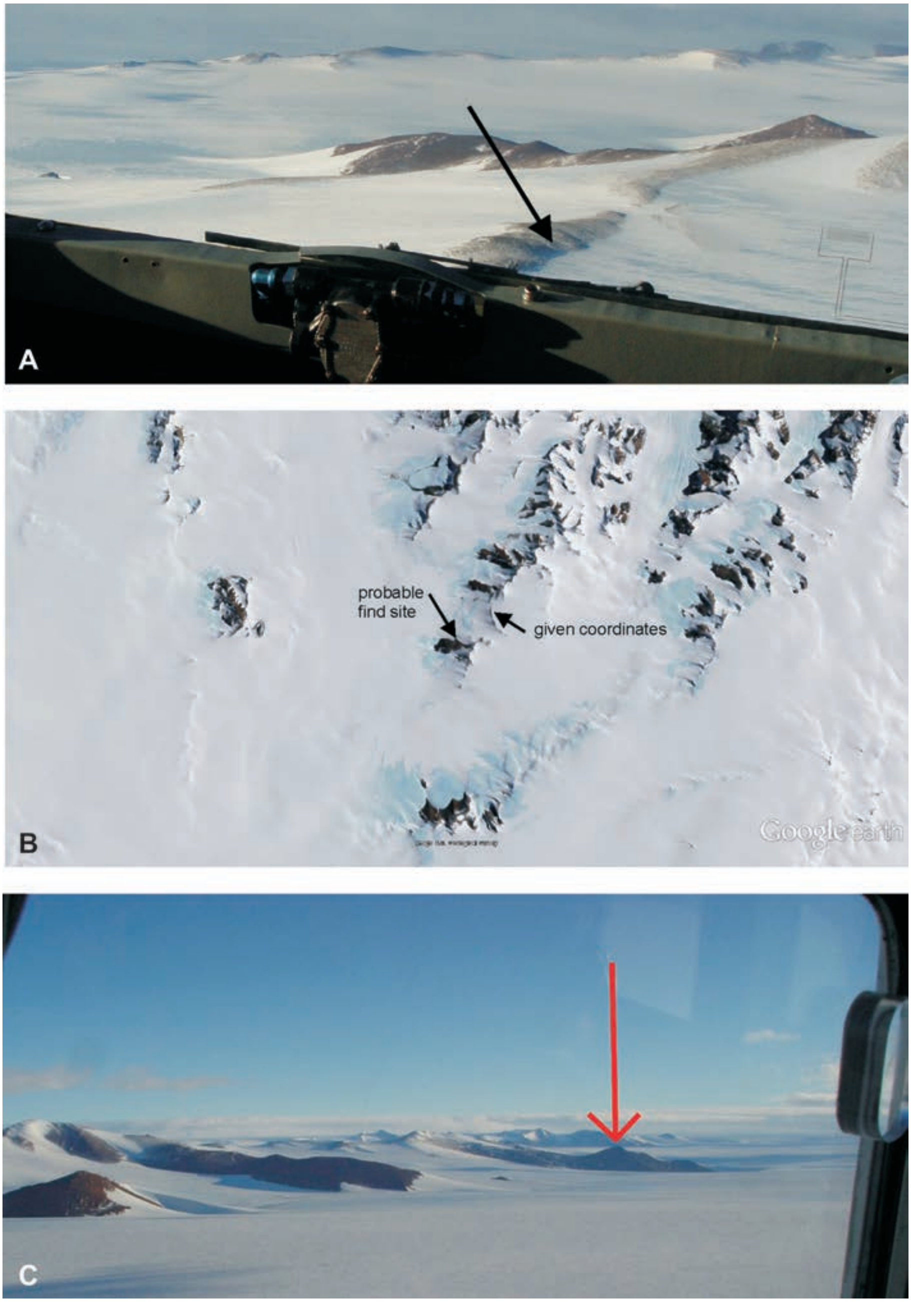

Fig. 8. Find site of the Lazarev meteorite. (a) Arrow indicating the in the literature given coordinates (71°57′ S, 11°31′ E). (b) The position given by Russian workers for the find site of the Lazarev meteorite is indicated by “given coordinates”. However, only the point indicated by “probable find site” does match the geologic description in the field book of RAVICH & REVNOV (1968), which initially reported this find. (c) Setting of the “probable” find site located at the flank of an isolated mountain. Map data: Google, U.S. Geological Survey.

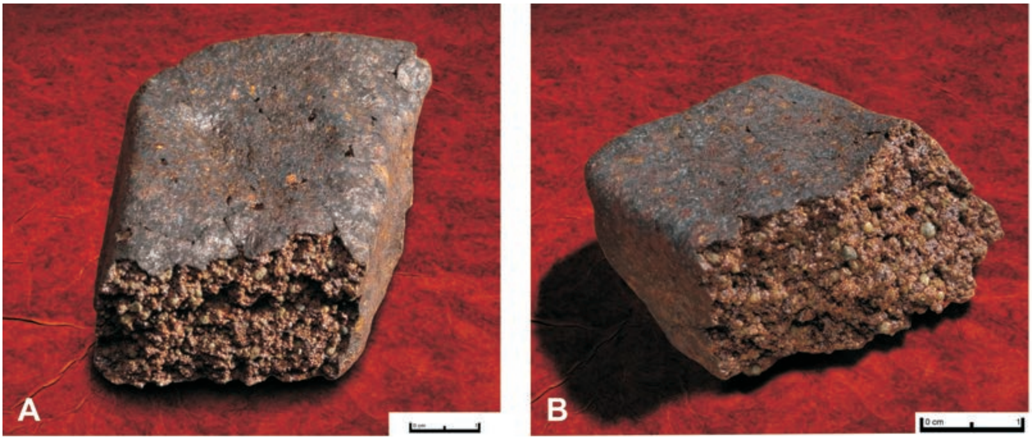

Fig. 9. Images of the fragments of meteorite STG 07013 with probably a very young terrestrial age (see text).

The indicated position of the Lazarev find location was overflown during the return trip from the Steingarden nunataks site. The arrow shown in Figure 8a points to the position, whose coordinates concur exactly with the numbers given by Ravich & Revnov (1968). Discrepancies between the given site description and the actual site were immediately noted. Neither an isolated mountain nor a steep slope exists at the given point. It appears probable that the given coordinates are of approximate nature. Based on the following three descriptors:

- isolated mountain,
- steep slope and
- association with an syenite outcrop,

it is proposed that the actual find site is near the point indicated in Fig. 8b under "probable find site". The key argument here is the fact that this location represents the only regional syenite outcrop. The nature of the "isolated mountain" is shown in Fig. 8c, which shows the syenite outcrop (red arrow).

A terrestrial age of the Lazarev meteorite of 5 Ma was determined by Nishiizumi *et al.* (1989). The regional ice divides upstream of this find site are located at a distance of ≤ 250 km (see, *e.g.*, Drewry 1983). Given typical ice velocities of Antarctic ice streams in excess of 1 m a^{-1} it appears plausible that this meteorite had spent most of its terrestrial existence at the find site. Plausibly, it should have arrived at the site during the Early to Middle Pliocene. If this assumption is correct, then we can conclude that the ice stand at that time was roughly the same as today and that no major higher ice stand has occurred at this site ever since. Otherwise, the meteorite would have been carried away by glacial erosion. The implication of near constant ice levels since the Pliocene would be that the suspected transport and emplacement mechanism of meteorites at this site has been operative since that time.

A second implication of near constant ice levels since the Pliocene would be that the regional ice stands are rather insensitive to climate change, a point that is further supported by results of modelling the reaction of the regional East Antarctic Ice sheet to climatic change, which implies nearly constant ice stand conditions (POLLARD & DECONTO 2009: fig. 1 therein). The find site very likely does not represent a direct fall of both Lazarev meteorite fragments (given the limited aerial extent of the outcrop in comparison to the vast surrounding ice fields). We consider, therefore, the whole neighbouring area as highly suspect to host meteorite concentrations. Unfortunately, one landing attempt to the west of this site failed due to the topographic roughness of blue ice fields nearby. One potential drawback of this area is the relative smallness of blue ice fields in relation to the extent of the snowfields.

Discussion

Seven meteorites from the Steingarden nunataks site (labelled 2–7, 11 in Fig. 2) were found on two elongated ice rises, of which one features a spare distribution of rock fragments on blue ice (the western rise), while the other one (the eastern rise) is covered by a veneer of rock fragments. It appears likely from the field impression that the rock fragments of the eastern rise are the result of glacial erosion from the sides or top of a small-scale topographic high to the south, which rises a few m above the current ice level. The rock drift near find site 5–7 includes m-sized boulders, while no more than dm-sized rocks were found in the find site 2–4. The rock fragment drifts are usually not further than about 1–1.5 km downstream of topographic highs and terminate rather abruptly. Assuming low ice flow rates (cm a^{-1}) for thin ice (see above radar data), the abrupt termination implies a rather young development of these drifts (formation during the last millennia (current warm stage?). A likely consequence of this hypothesis would be the assumption that slightly higher ice stands prevailed during the last cold stage with little to no erosion of these topographic high's taking place.

It is not readily explained why meteorites were preferably found along these rises but not in between. One conceivable model of ice flow – for which however no independent evidence exists – would envision a temporary coul de sac situation between the two ice rises during a time of a regionally higher ice stand (last cold stage?). Ice would flow into the dead end from the north and being sublimated exposing meteorites in the process. As the ice recedes, the coul de sac setting would vanish and the ice would revert and flow out to the north – more rapidly between the ice rises and more slowly from the flanks of the ice rises. This process would in principle favour a higher meteorite concentration along the flanks.

Two meteorites (labelled 8, 9 in Fig. 2; see also Fig. 3) were found on the lower extension of an elongated topographic step oriented roughly in east-west direction. The find sites are not located in a place that facilitates the formation of a meteorite concentration and appear to rest on a fringe of an ice stream from the Polar Plateau passing through the area. The regional ice slopes from the topographic step gently towards the north and towards an area of rapidly thickening ice. Apart from both meteorites, only few and large (mostly > 100 g) rock fragments rest on this blue ice field. Small rock fragments (wind blown fraction) are noticeably absent.

An extensive search of the area around find 10 (see Fig. 2), lasting for two days yielded disappointing results. The site is characterized by a blue ice depression covered with rock fragments. At first sight, the area seems to be well suited for the build-up of a meteorite concentration. The search results, however, argue against it.

A complete surprise was the find of meteorites 13 and 14 (see Fig. 2 and 9) in the immediate vicinity of the campsite of the expedition about four weeks after arrival and two days before departure from the site. Both meteorite fragments appeared very fresh. Each of the fragments, found about 50 m apart on blue ice, featured broken surface on one side. Both fragments were readily rejoined to one piece by placing the fractured surfaces side by side.

The flat blue ice fields in the area with the exception of the above discussed rock veneer sites near rock outcrops are conspicuously devoid of small frock fragments. The most of the time high winds in the region act apparently as a very effective agent to blow smaller objects across the ice surfaces, the regional topographic step and toward the crevassed areas downstream. We, therefore, never found any signs for an accumulation of wind-blown (meteorite) fragments. As open question remains, if later in the summer season such a site might become exposed as additional snow cover ablate away. Given the prevailing katabatic wind from the south, such a site should be located to the northwest of the investigated area which is however characterized by rapidly increasing ice thickness and moderate surface slopes (both preconditions for increased ice flow). The existence of a site with wind-blown meteorite fragment accumulation is, therefore, not very likely.

Our exposure ages determined for the nunataks near the Steingarden Nunataks site agree well with our earlier results from the Wohlthat Massiv area (Altmaier *et al.* 2010). It appears that the top of the outcrop of site 1 emerged out of the ice about 3–4 My ago The nunataks of site 2) emerged about 0.65 to 1.1 My ago. If the exposure of both outcrops occurred due to mountain uplift or reduction in ice thickness or both factors cannot be decided by our data. The data of both sites, however, implicate a rather thin regional ice thickness (and slow ice flow) for the last few 10^5 years in agreement with data from one aero-radar survey (one line) by Meyer *et al.* (2005) and one profile from this study.

Conclusions

The Queenmet-expedition has clarified several points:

(1) Meteorite concentrations on blue ice exist in Queen Maud Land.

(2) In comparison to other meteorite concentration sites in Antarctica (Cassidy *et al.* 1992) the meteorite concentration detected at the Steingarden Nunataks find site was rather low. Since the average weight of the recovered meteorites was unusually high in

comparison to other find sites, we propose that our find site is characterized by a lack of favourable glaciological situations for the development of catchment areas for wind-blown meteorite fragments, which typically make up the main portion of meteorite finds at other locations. This probably explains the observed low concentration.

(3) A second unfavourable factor for the accumulation of small-sized meteorites is given by frequent high wind speeds in the investigated area, which is fully exposed to the through-flow of katabatic winds from the Polar Plateau.

(4) The slow emergence of the regional nunataks out of the ice cover suggests a long-term (>several 10^5 years) similarity of the glaciological situation in the area. The explored sites show today features typical for Antarctic meteorite concentrations: ice thickness is greatly reduced (by air or ground radar investigated areas show less than 500 m ice thickness), blue ice surface slopes are gentle. Both factors point to slow ice flow.

(5) We have shown that the coordinates given for the find site of the Lazarev meteorite, discovered in 1961 by Russian workers, are not very accurate. A detailed comparison of the original description of the find site with the field situation indicates that the most likely find site is several km from the coordinates that were initially published.

(6) It is our impression that more blue ice fields to the south of the Wohlthat Massiv in Queen Maud Land potentially have meteorites.

(7) In total, 15 different meteorites were recovered, consisting of 14 stony meteorites and a 31 kg iron meteorite. For all stony meteorites bulk chemical compositions (26 major and trace elements), mineralogical data, and petrographic descriptions (including shock stages) are given. Based on the compositions of the ferromagnesian silicates and in accordance with the bulk chemistry data (considering the natural heterogeneity of the analysed samples), they were classified as ordinary chondrites, comprising 8 L chondrites, 5 H chondrites, and 1 LL chondrite.

Acknowledgments

We gratefully acknowledge funding of the Queenmet-expedition by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), as well as flight and logistic support provided by DROMLAN; D. MADER is thanked for help with the neutron activation analyses. We are grateful to the reviewers for helpful comments.

References

ALTMAIER, M., HERPERS, U., DELISLE, G., MERCHEL, S. & OTT, U. (2010): Glaciation history of Queen Maud Land (Antarctica) reconstructed from in-situ produced cosmogenic ^{10}Be, ^{26}Al and ^{21}Ne. – Polar Science, **4**/1: 42–61.

BUCHWALD, V.F. (1975): Handbook of iron meteorites. – 1416 pp., Berkeley and Los Angeles (University of California Press).

CASSIDY, W.A., HARVEY, R., SCHUTT, J., DELISLE, G. & YANAI, K. (1992): The meteorite collection sites of Antarctica. – Meteoritics, **27**/5: 490–525.

DELISLE, G. & SIEVERS, J. (1991): Subice topography and meteorite finds near the Allan Hills and the Near Western Icefield, Victoria Land, Antarctica. – Journal of Geophysical Research, **96**/E1: 15577–15587.

DELISLE, G. (1995): Storage of meteorites in Antarctic ice during glacial/interglacial stages. In: SCHULTZ, L., ANNEXSTAD, J.O., ZOLENSKY, M. (eds), Workshop on meteorites from cold and hot deserts. – LPI Technical Report, **95**-02: 26–27, Houston.

DREWRY, D.J. (1983): Antarctica: glaciological and geophysical folio. – Cambridge (Scott Polar Institute).

GRADY, M. (2002): Catalogue of Meteorites. – 689 pp., Cambridge (Cambridge University Press).

MADER, D. & KOEBERL, C. (2009): Using instrumental neutron activation analysis for geochemical analyses of terrestrial impact structures: Current analytical procedures at the University of Vienna gamma spectrometry laboratory. – Applied Radiation and Isotopes, **67**: 2100–2103.

MEYER, U., STEINHAGE, D., NIXDORF, U. & MILLER, H. (2005): Airborne Radio Echo Sounding Survey in Central Dronning Maud Land, East Antarctica. – Geologisches Jahrbuch der Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (BGR), **B 97**: 129–140.

NISHIIZUMI, K., ELMORE D., KUBIK P.W. (1989): Update on terrestrial ages of Antarctic meteorites. – Earth and Planetary Science Letters, **93**: 299–313.

PAECH, H.J., JACOBS, J., BAUER, W., MIKHALSKY, E., TALARICO, F., COLOMBO, F., ROLAND, N.W. & HENJES-KUNST, F. (2005): Geol. Map 1:500 000 of the Central Dronning Maud Land. In: PAECH H.-J. (ed.), International Geomaud Expedition of the BGR to Central Dronning Maud Land in 1995/96. – Geologisches Jahrbuch der Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (BGR) **B 97**: 407 pp., 4 maps.

POLLARD, D., DECONTO, R.M. (2009): Modelling West Antarctic ice sheet growth and collapse through the past five million years. – Nature, **458**: 329–332.

RAVICH, M.G. (1995): Field geological materials of the Russian Antarctic Expedition during the 1960–61 field season (observation points 701–887); Queen Maud Land / field geological observations. – 78 pp., St. Petersburg (Department of Antarctic Geology of VNIIO).

RAVICH, M.G. & REVNOV, B.I. (1968): Soviet geographical and geological investigations in Queen Maud Land. – International Geology Review, **10**/10: 1083–1095.

STÖFFLER, D., KEIL, K. & SCOTT, E.R.D. (1991): Shock metamorphism of ordinary chondrites. – Geochimica et Cosmochimica Acta, **55**: 3845–3867.

STRUB, E., WIESEL, H., DELISLE, G., BINNIE, S., LIERMANN, A., DUNAI, T., HERPERS, U., DEWALD, A., FEUERSTEIN, M., CHRISTL, M. & COENEN, H.H. (submitted): Glaciation history of Queen Maud Land (Antarctica) – new exposure data from nunataks. – Nuclear Instruments and Methods B.

VAN SCHMUS, W.R. & WOOD, J.A. (1967): A chemical-petrologic classification for the chondritic meteorites. – Geochimica et Cosmochimica Acta, **31**: 747–765.

WLOTZKA, F. (1993): A weathering scale for ordinary chondrites. – Meteoritics, **28**: 460.